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14. ABSTRACT

This report is the Final Report for this contract. It details the work done since our last progress report and provides a summary of all the achievements and results that we have obtained. In particular, it details our success in applying newly developed techniques from geometric invariant theory and shape theory, including discrimination metrics, to problems in target recognition. One of the most significant successes was the creation of a global theory of object/image equations for point features in the generalized weak perspective case. These equations offer a necessary and sufficient, pose independent, robust test for geometric consistency between an object and a purported image of that object. The work also included the development of optimal discrimination metrics and the proof of a metric duality result that shows one can work in either image space or object space to create a natural notion of distance between an object and an image. In addition, similar results were obtained in the radar case (orthographic projection) where the shape spaces, object/image equations, and metrics were worked out explicitly for small numbers of feature points.

15. SUBJECT TERMS

target recognition, object/image equations, discrimination metrics, shape spaces, shapelets

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"Aspects of Invariants for Object Recognition"

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Objectives: We begin by reminding the reader of the project's objectives as outlined in the original proposal. One particular area (1e. below) took on added importance as a result of several breakthroughs in our understanding of discrimination metrics and their application to target recognition systems. This area became a subject of greater emphasis as the project evolved. The original statement of work is included below.

"The following detailed list of tasks is proposed for this three-year effort. The research is being conducted at Texas A&M University, primarily by the principal investigator, Dr. Peter F. Stiller, and a number of graduate research assistants.

1. Develop a global (null space) approach to invariants and object/image equations and create a geometric framework for discrimination theory.

a. Provide a dictionary between the current algebraic approach and the new global approach.
b. Develop the necessary symbolic computational algorithms to handle computing the global object/image equations, either by improving the KSY resultant, fusing it with spare resultant techniques, or applying Plummer's technique.
c. Demonstrate that the global (null space) approach is more robust than current invariant methods for object recognition.
d. Explore the behavior of the global approach when dealing with multiplicities or geometric degeneracies (which cannot be handled with current methods).
e. Use the naturally occurring metrics (that arise in the global approach) to develop a robust discrimination theory.

2. Expand the applicability of the object/image formulation to more complex arrays of features in both EO (visible) and SAR imagery.

a. Investigate the method of back-projection through one sensor (using its appropriate object/image equations) and then forward projecting through the other sensor to analyze and describe mathematically cross-sensor invariance.
b. Investigate invariance for non-geometric quantities such as color and intensity.
c. Investigate extensions of the object/image theory that encompass 4D to 3D or 2D projections to handle motion and/or video.
d. Analyze the sensitivity of the object/image equations as configurations of features move toward special positions where the equations degenerate. This will require understanding the relationship between the natural distribution of feature sets versus the distribution of the invariants of those feature sets.

3. Geometric Hashing

a. Develop hashing algorithms that make use of the object/image relations to rapidly access databases of objects or images for recognition and/or image understanding purposes.
b. Test the efficiency of those algorithms.

d. Investigate the application of the hashing scheme to other relevant Air Force problems that involve the content-based retrieval of information from databases of images, schematics, design drawings, or geometric models. An example might be recognizing specific configurations of buildings in an urban environment.

4. Investigate specific Air Force applications

a. Develop the relevant sensor models and invariant theory. Find the analogues of the object/image relations.
b. Using appropriate noise models, analyze the robustness of the methods. Implement the algorithms.
c. Test real or synthetic data; for example, synthetic scattering data for SAR imagery generated using the XPATCH program."

Final Status of Effort: (For the period 12/1/00 to 5/31/04.)

At the time of this writing the project has been concluded. New funding in the form of a renewal grant has been awarded, assuring continuation of the research. In total the project ran for 42 months; the originally proposed 36 months plus a 6 month no cost extension.

We made substantial progress on virtually all of the originally proposed problems. This includes the understanding, development, and analysis of our global approach to invariants and object/image equations. It also includes our construction of a new class of discrimination metrics which are generalizations of the classical Procrustes metric of shape theory. In the first instance, we have provided a complete dictionary between the old algebraic approach and the new global approach. This has been worked out completely in the generalized weak perspective case and appears in our recent paper "Object/Image Relations, Shape Spaces, and Metrics." This new approach creates a geometric framework for discrimination theory and a more robust approach to recognition. Some of the main ideas and their application to the full perspective (optical) case were presented in our paper, "Global Invariant Methods for Object Recognition" described in a previous progress report. This approach also allows one to explore the behavior of recognition algorithms when dealing with multiplicities or geometric degeneracies (which cannot be handled with other methods). As described in our original proposal, one difficulty with the classical numerical invariants is that they are only rational functions on the appropriate quotient variety. As such, they are not always defined. This leads to serious numerical problems in the algorithms based on these invariants. To remedy these problems, we have succeeded in replacing these invariants by points in a Grassmann manifold in the weak perspective case, or by certain geometric objects, namely toric sub-varieties of Grassmannians, in the full perspective case. The object/image equations express certain incidence relations in the weak perspective case or become certain "resultant-like" expressions for the existence of a non-trivial intersection of the toric sub-varieties with certain Schubert varieties in the Grassmannian in the full perspective case. This "global" approach to invariants is providing more robust object recognition algorithms. Moreover, by representing the relevant the shape spaces as varieties

metric by restricting the standard Fubini-Study metric. These ideas are discussed in our paper "Object Recognition from a Global Geometric Perspective - Invariants and Metrics." This approach produces a natural metric on both the object and the image space that can be exploited to create an effective discrimination theory (i.e., a meaningful notation of "distance" between objects, between images, and between an object and an image.) We continue to tackle the symbolic computational problem of computing all of the new object/image equations for point features in the full perspective case. Finally, several new directions have emerged from this work. These directions includes future research on object/image equations for unordered point features to facilitate point cloud matching, research on object/image equations with parameters to handle articulation of objects, and investigations of invariant point to surface matching. All of these will expand the applicability and recognition power of our approach.

Accomplishments/Findings:

We report below on four significant areas of progress during the project.

1. The global (geometric) approach to invariants for object recognition.

These methods replaced an older ad hoc approach to object/image relations, which are the equations that relate features on 3D objects to analogous features in 2D images. The new theory is significant in that it gives a complete description of the geometric constraints that must hold between point and line features on an object in 3D and those features as they appear in 2D images of the object. These relations are completely view and pose independent and do not require any a priori knowledge of the camera parameters. The results have widespread application to object/target recognition algorithms, providing as they do, the most complete test for geometric consistency when attempting to match image features to a particular object.

One case where we have successfully and completely worked out and implemented the global theory is the case where we have point features under generalized weak perspective projection. Here the relevant group action on the feature sets is the affine group. Affine transformations consist of more than just rotations, reflections, translations and scale, so a certain amount of shearing is allowed. This is what accounts for the weak perspective effects.

A central result is that we can identify the shape spaces in this case with a well-known class of manifolds, namely Grassmannians and, via the Plucker embedding, produce global "shape coordinates" for each object shape and each image shape. These are homogeneous coordinates whose ratios are classical invariants of the action of the affine group on 3-space or 2-space. These classical invariants are of course rational functions in the data (coordinates of the points in our n-tuples.)

Also in this case, by exploiting certain incidence correspondences and the so-called Plucker relations, we were able to explicitly determine ALL of

perspective projection of the object shape. These relations are bihomogeneous polynomials in the two sets of shape coordinates - object and image. Moreover, because these relations form an ideal, it is sufficient to give just a (finite) set of generators to describe this infinite collection of relations. These polynomials, for point features in the generalized weak perspective case, are the global analogues of the old object/image relations. In simple terms, they express the necessary and sufficient conditions for object and image to match. They thus provide a geometric consistency test for matching the 3D data to the 2D data; which again is independent of the choice of coordinates. Moreover, if one fixes say the object shape, then the equations give us all image shapes produced by that object (the "image locus" of that object), and vice versa, if one fixes the image shape then the equations tell us all object shapes capable of projecting to that image (the "object locus" of that image.)

The key to this entire analysis is the geometry of the Grassmann manifolds. Unfortunately nothing similar exists in the orthographic or projective case. These cases are much harder to deal with; although in principle there is a global version of the theory in both cases. A complete theory in these cases requires formulating the results using the global differential geometry, topology, and algebraic geometry of the quotient spaces that are the shape spaces.

2. The Orthographic Case - Radar and Ladar

Radars and Ladars are known as orthographic sensors. This refers to the fact that the images they produce are orthographic projections of the 3D world. These images can be 1D, 2D, or 3D, and, much like an architect's drawing, size is known and parallel things remain parallel. These sensors collect a significant portion of the data that is used for Intelligence, Surveillance, and Reconnaissance (ISR).

An Automatic Target Recognition (ATR) capability is commonly needed to enable thorough and timely ISR. However, a general theory of discrimination (i.e. how to tell objects apart) is lacking. In our paper, "Geometric Methods for ATR - Invariants, Object-Image Equations, and Metrics" joint with Dr. Greg Arnold of the Air Force Research Laboratory, Wright Patterson AFB, we began the task of developing the fundamentals of a discrimination theory for generic orthographic systems.

Our preliminary work offers promising new results toward a comprehensive theory of measuring the geometric differences between shapes (of objects of interest and their images) in radar and ladar applications. These initial results explicitly work out the details of the global shape space and object/image formulation for small numbers of feature points in the 2D to 1D radar (orthographic) case. For more feature points we understand the topology of the shape spaces, but not their isometric embeddings into an ambient Euclidean space. In 3D we have only an incomplete description of the shape spaces. More work needs to be done so that we can actually implement these ideas in practice.

3. Metrics

Our global theory leads naturally to metrics on the object and the image space that can be exploited to create an effective discrimination theory (i.e., a meaningful notation of "distance" between objects and between images). These metrics are related to the Fubini-Study metrics on the standard Grassmannians and the Procrustes metric of classical shape theory for the similarity group. These metrics can be shown to be, in a certain sense, optimal and related to classical metrics in computer vision.

What exactly do we mean by a metric? Basically, we would like to know if two configurations of a fixed number of points in 3D (or 2D) are the same up to some allowable group of transformations. The groups we have been concerned with are the Euclidean, similarity, affine, and perspective (projective general linear.) If they are the same, then we want a distance of zero, and if not, we want a distance that expresses their dissimilarity - always recognizing that we can transform the points. One approach to creating a metric is to try to make sense of the minimum distance between the orbits of two configurations of features (tuples of points in this discussion.) That of course assumes that we have a natural notion of distance on the space of geometric configurations and that we have accounted for things like scale. Under some conditions such a notion of distance provides a metric on the quotient space, i.e. on configurations mod the group action, which we call the space of object or image shapes (shape space, or object space, or image space for short.)

We investigated these quotient metrics (also called orbit metrics) on the object and image shape spaces. For point features these metrics are derived from the standard L2-metric on n-tuples of feature points. On the object or image shape space these are usually Riemannian metrics apart from some manageable singularities. A known example of such a metric is the Procrustes metric of classical shape theory. It provides a metric on configurations of point features under the allowable transformations of rotation, scale, and translation (i.e. the similarity group.)

A successful result is our metric in the generalized weak perspective case. It is a generalization of the classical Procrustes metric and comes from the Fubini-Study metrics on the standard Grassmannians. (It is known that the Procrustes metric used in statistical shape theory is related to the Fubini-Study metric on projective space.) This leads us to conclude that our metric in the generalized weak perspective case is the right generalization, and that it will be, in a certain sense, optimal and related to classical metrics in computer vision.

While there is more to discover in the orthographic cases (used for radar applications), the primary unsolved case, as far as metrics are concerned, is that of point features in full perspective, which is applicable to optical sensors. Our approach in this case involves embedding the shape space into a large dimensional projective space where it will acquire a metric via the restriction of the Fubini-Study metric on the projective

where we have been able to isometrically embed the shape space in Euclidean space.

4. Metric Duality Theorem

Having defined metrics on the shape spaces, we were able to produce a notion of distance between two object shapes or between two image shapes. We then coupled these metrics with the object image relations to get two notions of "distance" between an object and an image (with zero being a match under our particular projection). We either define the distance in object space as the minimum distance between the given object and all objects capable of producing the given image, or we work in image space and define the distance to be the minimum between the given image and all images produced by the given object. An important Duality Theorem was proved in the weak perspective case which shows these two notions of "distance" between an object and an image are equal! This important result appears to hold in much greater generality.

Personnel Supported:

In addition to the principal investigator, who was partially supported on the project during the summers, the project, over the past three years, has provided support for four graduate research assistants: Mr. Robert Ruffley, Mr. Jody Wilson, Mr. Kevin Abbott, and Ms. Jennifer Snodgrass, all graduate students in the Mathematics Department at Texas A&M University. They have been engaged in the coding and testing of a number of algorithms and in the design of computational experiments to verify various theoretical ideas that emerged during the course of the research. Mr. Wilson received his Master's degree in Mathematics in August 2003 and is now employed in the software industry in California. Ms. Snodgrass, who received her Bachelor's degree in Applied Mathematics from Rice University, joined the project in the Fall of 2003. Most recently, Mr. Abbott, a Ph.D. student in Mathematics, has become involved in the project as a result of a graduate course in Shape Theory offered by the P.I. Dr. Stiller in the Spring of 2004. This course presented the results of this research along with background material in differential geometry and statistical shape theory.

Faculty: Dr. Peter F. Stiller, Prof. of Mathematics and Computer Science

Graduate Students: Robert Ruffley, Jody Wilson, Jennifer Snodgrass, Kevin Abbott

Publications:

A number of papers dealing with this project's results have appeared in print (copies of which were attached to previous reports.) Three additional papers are completed and have been or will soon be submitted for publication. Two additional papers are in preparation.

Stiller, P. F., "The Relationship Between Shape under Similarity Transformations and Shape under Affine Transformations," Proceedings SPIE Int'l Symposium on Optical Science and Technology, Mathematics of

Stiller, P.F., "Object Image Relations and Vision Metrics II," Proceedings of IS&T/SPIE 16th International Symposium Electronic Imaging: Science and Technology, Vision Geometry XII, Vol. 5300, January 2004, San Jose, California, pp. 74-85 (2004).

Stiller, P. F., "Object/Image Relations and Vision Metrics I," Proceedings SPIE Int'l Symposium on Optical Science and Technology, Mathematics of Data/Image Coding, Compression, and Encryption, with Applications, Vol. 5208, Mark Schmalz; Ed, San Diego, CA, 8/03, pp. 165-178 (2003).

Stiller, P. F., "Object recognition from a global geometric perspective: invariants and metrics," Proceedings SPIE Int'l Conf., Vision Geometry XI, Vol. 4794, Seattle, WA, 7/02, pp. 71-80 (2002).

Schenck, H. and Stiller, P. F., "Cohomology Vanishing and a Problem in Approximation Theory," Manuscripta Mathematica, Vol. 107, No.1, pp. 43-58 (2002).

Stiller, P. F., "Global Invariant Methods for Object Recognition," Proceedings SPIE Int'l Conf., Vision Geometry X, Vol. 4476, San Diego, CA, 7/01, pp. 13-21 (2001).

Arnold, G. and Stiller, P.F., "Geometric Methods for ATR - Invariants, Object Image Equations and Metrics," to be submitted to an IEEE Journal.

Stiller, P.F., "Object/Image Relations, Shape Spaces, and Metrics: The Generalized Weak Perspective Case," preprint.

Stiller, P.F., "Perspective Shape Spaces and Object Recognition," in preparation

Stiller, P.F., "Vision Metrics for Object Recognition," in preparation.

Interactions/Transitions:

In November 2000, just prior to the start of this project, Dr. Stiller participated in the Air Force Scientific Advisory Board (SAB) review of the Air Force Research Laboratory's Target Recognition Branch. He was able to present the results of his previous research and collaboration with researchers at AFRL (Dr. Vince Velten, Dr. Greg Arnold, and Dr. Kirk Sturtz) and to discuss the new research directions in the current project. He was able to also discuss this effort with Dr. Mark Grundeisen, AFOSR.

Following the SAB, Dr. Stiller spent two days at AFRL, Wright Patterson AFB, and gave a colloquium at the Air Force Institute of Technology at the invitation of Dr. Mark Oxley of AFIT's Department of Mathematics and Statistics. His talk was entitled "Applications of Geometric Invariants to

In March 2001, Dr. Stiller hosted Dr. Greg Arnold and Dr. Kirk Sturtz from the Air Force Research Laboratory's Target Recognition Branch AFRL/SNAT, at Texas A&M. During the visit, Dr. Stiller outlined the progress toward the developing the global theory of object/image relations. The group also discussed various approaches to developing reliable metrics for target recognition, and Dr. Stiller presented ideas related to using the Fubini-Study metric in object space and in image space to properly measure feature differences.

In July 2001, Dr. Stiller attended the SPIE International Conference on Optical Science and Technology in San Diego for the conference on Vision Geometry (Vision Geometry X). Dr. Stiller presented a paper entitled "Global Invariant Methods for Object Recognition," in the session on Invariants and chaired the session on Object Surfaces. Dr. Stiller and other conference organizers held meetings on the formation of a Vision Geometry working group to seek permanent funding to expand the Vision Geometry Conferences and to add a series of workshops on topics that would focus on geometric methods (differential geometric, algebro-geometric and invariant theoretic) in vision and object recognition and on digital geometry.

In August 2001, Dr. Stiller attended the First Annual Automatic Target Recognition Theory Workshop at Wright State University in Dayton, Ohio. See www.mbvlab.wpafb.af.mil/Compase/ATRTheory/ for conference details. Dr. Stiller spoke on "Single View Recognition from a Theoretical Viewpoint." After the conference, Dr. Stiller visited AFRL's Target Recognition Branch to discuss the recent results obtained as part of this project. During the course of discussions with Dr. Greg Arnold and Dr. Kirk Sturtz at AFRL, a new approach to metrics for object recognition was proposed.

In July 2002, Dr. Stiller attended the SPIE International Conference on Optical Science and Technology in Seattle for the conference on Vision Geometry (Vision Geometry XI). Dr. Stiller presented a paper entitled "Object Recognition from a Global Geometric Perspective."

At the end of August 2002, Dr. Stiller again visited the Air Force Research Laboratory's Target Recognition Branch AFRL/SNAT for a week. Dr. Stiller outlined his continued progress on global object/image relations. During the course of discussions with Dr. Greg Arnold and Dr. Kirk Sturtz at AFRL, an approach to object/image equations for unordered (unlabeled) features was proposed and an initial example was worked out in detail.

In October 2002, Dr. Stiller participated in the Air Force Scientific Advisory Board (SAB) review of the Air Force Research Laboratory's Target Recognition Branch. He was a featured speaker talking on "Geometric Methods for ATR" at the invitation of Dr. Jon Sjogren, AFOSR. Prior to the SAB, Dr. Stiller spent three days working with researchers at AFRL and discussing his approach to realizing perspective shape space as a subvariety of projective space, thereby creating a discrimination metric that extends the classical Procrustes metric of Shape Theory to the full perspective case.

In May and June 2003, Dr. Stiller again visited the Air Force Research Laboratory's Target Recognition Branch AFRL/SNAT. During this time work on a joint paper, "Geometric Methods for ATR - Invariants, Object-Image Equations and Metrics," with Dr. Greg Arnold was completed. Dr. Stiller made two presentations of this research to the Target Recognition Branch AFRL/SNAT. The second presentation was open to the entire Lab and had overflow attendance.

Dr. Stiller attended the AFOSR Program Review at Princeton University, June 5-7, 2003. The meeting was hosted by Dr. Jon Sjogren, AFOSR and Professor Ingrid Daubechies, Princeton University. Dr. Stiller spoke on "Shape Spaces, Object-Image Varieties, and Metrics for Object Recognition" jointly with Dr. Greg Arnold, AFRL/SNAT.

In August 2003, Dr. Stiller attended the SPIE International Conference on Optical Science and Technology in San Diego for the conference on Mathematics of Data/Image Encoding, Compression, and Encryption VI, with Applications. He presented a paper entitled "Object/Image Relations and Vision Metrics I." At the meeting, Dr. Stiller discussed with Dr. Mark Schmaltz of Florida State University, a possible novel application of his research on metrics for object recognition to the completely different problem of evaluating data compression and encryption schemes.

In January 2004, Dr. Greg Arnold and Dr. Kirk Sturtz from AFRL/SN at Wright Patterson AFB, and Dr. T. J. Klausutis from Eglin AFB visited Texas A&M to discuss issues around discrimination metrics. Problems related to point cloud matching were also discussed.

Also in January 2004 Dr. Stiller presented a paper at Vision Geometry XII, a
conference at the SPIE 16th International Symposium on Electronic Imaging: Science and Technology held in San Jose, CA.

In May 2004 Dr. Stiller again visited Air Force Research Laboratory's Target Recognition Branch AFRL/SNAT where a final report on the project's results was made and new topics for future research and collaboration were discussed.

New Discoveries, Inventions, or Patent Disclosures:

Beyond the research results discussed above, there are no new discoveries, inventions, or patent disclosures.

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